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6. AUTHOR(S)
J. E. Thomas

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Duke University
Physics Department, Box 90305
Durham, NC 27708-0305

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13. ABSTRACT (Maximum 200 words)

Three major results of this program are described:
i) Raman-induced resonance imaging is used to measure the distribution of atoms in a magneto-optical trap;
ii) Nonoptical sources of heating in atom traps are explored theoretically, including laser-noise induced heating in optical traps and quantum-diffractive background gas collision-induced heating in shallow magnetic or optical traps;
iii) An ultrastable CO_2 laser trap is demonstrated that achieves a 1/e lifetime of 300 sec, the longest ever obtained with an all-optical trap. This enables exploration of s-wave interactions in a weakly interacting, ultracold Fermi gas.

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Contents

1 Manuscripts Submitted or Published Under ARO Sponsorship During This Reporting Period

1) T. A. Savard, C. A Baird, K. M. O'Hara, and J. E. Thomas, "A Multi-coil Zeeman Slower," OSA Technical Digest Series (Optical Society of America, Washington, D.C.,1997) **12**, 107-108 (1997).
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10) K. M. O'Hara, S. R. Granade, M. E. Gehm, T. A. Savard, S. Bali, and J. E. Thomas, "Ultrastable CO_2 Laser Trapping of Lithium Fermions," Bull. Am. Phys. Soc. **44**, 269 (1999).
11) T. A. Savard, K. M. O'Hara, and J. E. Thomas, "Laser-noise-induced Heating in Far-off Resonance Optical Traps," Phys. Rev. A **56**, R1095 (1997).
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14) S. Bali, K. M. O'Hara, M. E. Gehm, S. R. Granade, and J. E. Thomas, "Quantum-diffractive Background Gas Collisions in Atom-trap Heating and Loss," Phys. Rev. A **60**, R29 (1999).

2 Scientific Personnel Supported by This Project and Degrees Awarded During This Reporting Period

J.E.Thomas
T. Savard (Graduate Student, Ph.D., May, 1998)
K. O'Hara (Graduate Student)
S. Granade (Graduate Student)
M. Gehm (Graduate Student)
S. Bali (Post doctoral associate)

3 Report of Inventions

None.

4 Scientific Progress and Accomplishments

In this program two major experimental goals and two important theoretical studies have been accomplished in the past three years. The first major experimental accomplishment is the is the development of a state-of-the-art atom trapping system. This system was used to demonstrate Raman induced resonance imaging of lithium atoms in a magneto-otical trap and formed the basis for Tom Savard's Ph D. thesis. During this period, the principal investigator was made a Fellow of the American Physical Society, largely for the development of precision atom imaging methods in this and the previous ARO sponsored program.

Theoretical models were developed for laser noise-induced heating in all-optical traps. This lead to an improved understanding of the role of trap noise induced heating in both optical and magnetic traps. In addition, a model was developed for heating arising from quantum-diffractive background gas collisions. Together, these results provide a framework for predicting non-optical heating rates which have limited all-optical and magnetic traps. This framework has proven important for understanding and eliminating residual heating rates that have plagued previous all-optical traps.

Armed with this knowledge, a second important experimental result was accomplished in developing an ultrastable CO_2 laser trap to explore the fundamental physics

of ultracold fermions. This trap has been used to store ^{6}Li fermions with a trap $1/e$ lifetime of 300 seconds, nearly two orders of magnitude longer than previous all-optical traps. The new trap enables direct evaporative cooling in a two-state fermionic system and will be used for a number of important experiments.

4.1 Overview

This program evolved out of an ongoing effort to develop precision methods for position measurement of *moving* atoms in beams and traps. Precision position measurement and localization of atoms has diverse applications in atom optics. These range from direct-writing neutral atom nanolithography [1] to new fundamental studies of quantum correlations in ultracold, dilute samples of bosons or fermions [2, 3, 4, 5, 6]. Further, textbook examples of quantum measurement are enabled by position-dependent atom-field couplings which entangle the atomic internal and center-of-mass states [7, 8]. To fully explore these applications, new methods of imaging moving atoms are needed that have the potential to achieve both sub-de Broglie wavelength and suboptical wavelength resolution [2, 3].

For this purpose, we have explored methods of measuring atomic position distributions by using resonance imaging in ultrahigh potential gradients. Generally, these techniques employ Raman induced transitions between long lived atomic ground state sublevels to achieve high frequency resolution. High spatial resolution is achieved using a large potential gradient that causes the Raman transition frequency to be position dependent. The atomic position distribution is therefore encoded in the Raman frequency distribution. We have demonstrated this method using both high magnetic field gradients and optically generated potential gradients, i.e., light-shift gradients. The latter has enabled sub-optical wavelength position resolution. For a review, see Ref. [3]. In the ideal case, this method has the unique feature that the momentum spread imparted to the atom during the position measurement is due to the potential gradient. In this limit, the measurement accuracy is determined by the Heisenberg uncertainty principle and the method can achieve resolution in the ten nanometer range. We have coined the name "quantum resonance imaging," for this method.

Ultracold weakly interacting atomic vapors provide particularly exciting opportunities for application of precision resonance imaging methods. Of special interest at the present time are two-state fermionic atoms, which are expected to undergo a BCS transition at low temperature. To explore two-state fermionic systems, we developed a unique ultrastable CO_2 laser trap and applied it to the fermionic ^{6}Li system [9]. As a result of the extremely large detuning and long wavelength for the CO_2 laser trap, the optical scattering rate is only one photon per atom per *hour*, so that optical heating is negligible. Hence, this trap enables storage of arbitrary spin states in nearly identical, conservative potentials. However, optical traps have suffered from

unexplained heating rates that limit storage times to a few seconds in an ultrahigh vacuum [10]. Recently, we developed a theory of trap-noise induced heating for optical traps that are not limited by optical heating rates. We showed that to achieve long storage times and low residual heating rates, heating arising from laser intensity noise and beam pointing noise must be stringently controlled [11, 12]. We also showed that quantum-diffractive background gas collisions produce a residual heating rate as well as the dominant loss rate in shallow atom traps [13]. The ultrastable CO_2 laser trap achieves noise induced heating times of several hours. Hence, in an ultrahigh vacuum, extremely long storage times and low heating rates are possible. We demonstrated an improvement in storage time over previous optical traps by nearly two orders of magnitude, achieving a 1/e trap lifetime of 300 seconds [9]. By trapping two hyperfine sublevels of the ^{6}Li ground state, this method enables s-wave scattering interactions. These interactions can be exploited to achieve rapid evaporative cooling and potentially spin pairing at sufficiently low temperature. This is the goal of the current ARO sponsored research.

The spectacular results attained using the ultrastable CO_2 laser trap have been highlighted in Physical Review Focus, on the Science Magazine Website, and in a CERN newsletter.

4.2 Magnetic Resonance Imaging of Atoms in MOT

In the first part of this program, we applied Raman-induced resonance imaging to a cloud of ^{6}Li atoms in a magneto-optical trap (MOT) to determine the size of the position distribution and the location of the centroid. The magnetic field gradient of the MOT itself provides the necessary position-dependent potential. Using this method, atomic positions are determined with respect to the magnetic field zero point with a resolution of 12 μm. The shapes of the Raman spectra are found to be quite sensitive to the size of the cloud and the direction and magnitude of the offset of the centroid. Improvements can be made to surpass the typical resolution of several microns achieved by CCD-based absorption/fluorescence imaging [14, 15].

The Raman imaging technique is applicable to both optically thin and optically thick samples. In the latter case, the high spectral resolution of the Raman method ensures that the fields interact with only a small number of atoms, minimizing distortion arising from absorption. We have shown how unwanted spatially-varying light shifts from the Raman fields can be eliminated and we have derived the general structure of the Raman transition probability for alkali-metal atoms in a magnetic field gradient. This research comprised the Ph. D. thesis dissertation for Tom Savard. These experiments serve as a starting point for the development of general resonance imaging methods that will enable the measurement of position distributions and state-dependent spatial correlations of atoms in ultracold vapors with suboptical

wavelength, uncertainty-principle-limited precision [3].

4.3 Theory of Non-optical Heating Rates in Atom Traps

For many years, optical traps were known to suffer from unexplained heating mechanisms that limit the minimum residual heating rates and the maximum storage times in an ultrahigh vacuum. Typical storage times were limited to a few seconds, although the collision-induced loss rate was expected to yield trap lifetimes of several hundred seconds in an ultrahigh vacuum [10]. While it was appreciated that trap noise could cause heating, it was generally accepted that the heating rate was negligible.

Recently, we developed a simple theory of trap-noise induced heating using a simple harmonic oscillator model. We showed that fluctuations in the trap spring constant cause exponential heating while fluctuations in the trap position cause heating at a constant rate [11]. For optical traps, the former arises from fluctuations in the trap laser intensity while the latter arises from laser beam pointing noise. We found that the heating rates are strongly dependent on the trap resonance frequency. For low frequency traps, force fluctuations are only weakly transmitted to the atoms. For this reason, the required stability of magnetic traps, as used in BEC experiments, is not too stringent. By contrast, tightly confining optical traps with high resonance frequencies are very susceptible to noise-induced heating. In this case, the laser power and beam direction must be carefully controlled.

Using the harmonic oscillator model, we developed a theory of trap noise-induced heating dynamics [12]. We showed that the energy distribution in the trap tends to evolve into a single eigenmode. The mean energy tends to a constant value, while atoms continually escape from the trap as a result of the heat input. We showed that noise induced heating leads generally to a multimode decay curve.

We also have explored loss and heating which arise from quantum-diffractive background gas collisions [13]. We showed that the energy imparted to a trapped atom by a diffractive background gas collision is typically large compared to the depth of most magnetic and optical traps. In this case, the loss rate is determined by the total collision cross section. Collisions that leave kicked atoms in the trap cause heating. The heating rate is found to scale as the square of the well depth. The calculated heating rate was found to explain the residual heating rate observed in a recent Raman cooling experiment by the Stanford group. These small diffractive heating rates determine the quantum limit on the insulation of a vacuum at finite pressure, and may limit the ultimate phase space density achievable in low temperature trap experiments.

4.4 Ultrastable CO_2 Laser Trapping of Lithium Fermions

CO_2 laser traps have been shown to exhibit very low optical scattering rates as a result of the large detuning and low optical frequency. The scattering rate is determined by the Larmor cross section and typically is limited to the order of a photon per atom per hour. Such traps are ideal for trapping multiple spin states, since the large detuning also assures that the trapping potential is nearly independent of the ground hyperfine state. Hence, CO_2 laser traps are well suited for exploring s-wave interactions between cold fermions, where the exclusion principle requires an antisymmetric spin state.

Our theoretical model of laser-noise-induced heating in optical traps showed that stringent requirements are placed on the laser stability to achieve low heating rates and long trap lifetimes. We knew that CO_2 lasers are therefore well suited for optical traps, since they are inherently stable and very powerful. With proper design, CO_2 lasers can be made extremely stable, enabling ultrastable optical traps to be developed. By employing an ultrahigh vacuum of 10^{-11} Torr, heating and loss arising from background gas collisions can be suppressed.

We demonstrated ultrastable CO_2 laser trapping of lithium fermions. The system achieved a trap 1/e lifetime of 300 seconds, consistent with the background limited loss rate at 10^{-11}. This result constitutes the first experimental proof of principle that all-optical traps can achieve extremely long storage times, a goal that has been sought for many years. Since multiple spin states have been trapped, this paves the way for exploring s-wave interactions in an ultracold fermionic system, which is the primary goal of the current ARO sponsored program.

4.5 Additional Research Supported in Part by ARO

In addition to the experiments described above, we have obtained important results in one other program which has been supported in part by this grant.

Phase-dependent Resonance Fluorescence

We have developed novel methods of studying phase-dependent optical noise in the radiation of coherently prepared atomic systems. The study of phase-dependent quantum noise in resonance fluorescence and in particular the observation of *squeezing* in phase-dependent resonance fluorescence has remained an open problem for some time, since the first predictions in 1981. The purpose of our work has been to elucidate the quantum sources of atom noise by direct measurement and physical interpretation. The results of this work will have impact on the optical methods we are developing for precision measurement of position distributions and spatial correlations in cold atom samples. These studies have resulted in important publications

in Physical Review A and in Physical Review Letters which are listed in the § 1.

5 Technological Applications

Optical manipulation of atomic wavefronts is being explored as a means of direct writing neutral atom lithography by a number of groups in this country and abroad. The suboptical wavelength atom imaging methods that have been explored as a part of this research will be important for a variety of applications to novel microfabrication methods including:

i) characterization of neutral atom beams which are transversely cooled and focussed by optical methods.
ii) characterization of atom beams transmitted through hollow-core fibers.
iii) development of "adaptive" atom optics based on position dependent depletion of atomic wavefronts– on a suboptical wavelength scale.
iv) development of suboptical wavelength scale "position dependent chemistry," by combining state selective chemical reactions with techniques of state selective atomic localization.

Our current experiments explore the dynamics of an ultracold, trapped fermionic vapor. Potentially, these studies will enable exploration of the BCS transition in a weakly interacting vapor with tunable interactions. This is likely to lead to new and fundamental insights into the theory of superconductivity. Further, since the CO_2 laser enables trapping of both atoms and molecules, our experiments are well suited for exploring novel matter-wave-optical processes, such as coherent changes of statistics by transitions between free fermionic atoms and bosonic molecules, where novel many body quantum dynamics is expected. Such studies will enable the exploration of nonlinear atom/molecular-wave-optical processes, enabling new techniques for manipulation and control of matter-wave fields.

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A Selected Reprints/Preprints

The following reprints/preprints are included with this report:

1) T. A. Savard, K. M. O'Hara, and J. E. Thomas, "Laser-noise-induced Heating in Far-off Resonance Optical Traps," Phys. Rev. A **56**, R1095 (1997).

2) M. E. Gehm, K. M. O'Hara, T. A. Savard, and J. E. Thomas, "Dynamics of Noise Induced Heating in Atom Traps," Phys. Rev. A **58**, 3914 (1998).

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4) S. Bali, K. M. O'Hara, M. E. Gehm, S. R. Granade, and J. E. Thomas, "Quantum-diffractive Background Gas Collisions in Atom-trap Heating and Loss," Phys. Rev. A **60**, R29 (1999).